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Dose Reduction Factors Between Different Source Terms in a Cask

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DISCLAIMER

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ACRONYMS AND ABBREVIATIONS

ACRONYMS

ANS	American Nuclear Society
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BSC	Bechtel SAIC Company, LLC
BWR	Boiling Water Reactor
CD	Compact disc
CSNF	Commercial Spent Nuclear Fuel
DB	Design Basis
DOE	U. S. Department of Energy
DPC	Dual Purpose Canister
NRC	U. S. Nuclear Regulatory Commission
PCSA	Preclosure Safety Analysis
PWR	Pressurized Water Reactor
RPM	Repository Project Management
SNF	Spent Nuclear Fuel
SS 316	Stainless Steel 316
TAD	Transportation, Aging, and Disposal
WP	Waste Package
YMP	Yucca Mountain Project

ABBREVIATIONS and UNITS

b	barn
cm	centimeter

g	gram
GWd	gigawatt-day
hr	hour
in.	inch
kg	kilogram
m	meter
mrem	millirem
MeV	million electron volt
MTU	metric ton uranium
s	second

1. PURPOSE

The purpose of this calculation is to calculate the dose rates of two conceptual transportation casks each carrying a Transportation, Aging, and Disposal (TAD) canister separately loaded with the average, design basis (DB), and maximum commercial spent nuclear fuel (CSNF) assemblies. Then, the dose-rate reduction factors between the maximum and the design basis fuels, the design basis and the average fuels, and the maximum and the average fuels are computed.

The results of this calculation may be used to substantiate the dose-rate reduction factors such as those in the engineering study *Repository ALARA Goal Compliance* (Reference 2.2.7), which is cited as a reference in a Preclosure Safety Analyses (PCSA) calculation that supports the License Application.

The calculations contained in this document are developed by Nuclear and Radiological Engineering of the Repository Project Management (RPM) organization. Yucca Mountain Project (YMP) personnel from Nuclear and Radiological Engineering should be consulted before use of the calculations for purposes other than those stated herein or use by individuals other than personnel in Nuclear and Radiological Engineering.

2. REFERENCES

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2.1.2 EG-PRO-3DP-G04B-00037 Rev 14. *Calculations and Analyses.* Las Vegas, Nevada: Bechtel SAIC Company.

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2.2.28 Sisley, S.E. 2002. "Transportation License Application for the FuelSolutions™ System (TAC No. L23311), Submittal of the FuelSolution™ Transportation SARs, Revision 3." Letter from S.E. Sisley (BNFL) to the NRC, April 11, 2002, BFS/NRC 02-011, with enclosures. TIC: 255245. [DIRS 171545].

NOTE: Reference 2.2.20 is a direct input, but is not QA: QA. It is justified as acceptable for the intended use, as it is directly from the DOE and is considered the best available data on the subject. The referenced values, cited in Tables 3 and 4, are valid for use since they are reliable and reasonable based on engineering judgment.

2.3 DESIGN CONSTRAINTS

2.3.1 10 CFR 71. 2008. Energy: Packaging and Transportation of Radioactive Material. Internet Accessible. [DIRS 185678].

2.4 DESIGN OUTPUTS

The results of this calculation will be used to substantiate the dose reduction factor in the *Repository ALARA Goal Compliance* (Reference 2.2.7), which is cited as a reference in a PCSA calculation that supports the License Application.

3. ASSUMPTIONS

3.1 ASSUMPTIONS REQUIRING VERIFICATION

None

3.2 ASSUMPTIONS NOT REQUIRING VERIFICATION

Assumptions 3.2.1, 3.2.2, and 3.2.3 are modeling assumptions and do not require further verification. The materials and dimensions for the TAD canister and for the conceptual transportation casks are only selected to characterize two transportation casks that meet 10 CFR71.47 (Reference 2.3.1) dose rates when loaded with the “maximum” and “average” pressurized water reactor (PWR) assemblies, respectively. There is no need to verify those dimensions or materials at a later date. The calculated results in Section 7.1.1 verify that the conceptual casks would meet 10 CFR 71.47 (Reference 2.3.1) dose rates.

3.2.1 Material and Wall Thickness of TAD Canister

Assumption: It is assumed that the TAD canister is made of stainless steel 316 (SS 316) and has a wall thickness of 0.25 in. for the radial and bottom shells.

Rationale: Currently, the design of the TAD canister does not exist. Based on a survey of existing multipurpose and dual purpose canisters (DPC) (Reference 2.2.14, p. 56), a 0.25 in. thickness is below the wall thickness of any existing canisters. For the purpose of this calculation, this assumption leads to higher and conservative external dose rates. Since SS 316 is the same material used for the waste package inner shell, it is a logical choice for the TAD canister.

Although Reference 2.2.14 is an engineering study with a QA: N/A status, it is used here as an indirect input to support the assumption, which is conservative for dose rate calculations.

Usage: This assumption is used in Sections 6.2.1 and 6.2.5.

3.2.2 Material and Thickness of TAD Shield Plug

Assumption: It is assumed that the TAD shield plug is made of SS 316 and has a thickness of 11 in.

Rationale: Currently, the design of the TAD canister does not exist. A thick shield plug of 11 in. (Reference 2.2.15, Table 12) is needed to keep the maximum contact dose rate of the top surface below 1000 mrem/hr (Reference 2.2.22, Section 3.1.4). Since SS 316 is the same material used for the waste package inner shell, it is a logical choice for the TAD shield plug.

Usage: This assumption is used in Section 6.2.1.

3.2.3 Geometry and Materials of Conceptual TAD Transportation Casks

Assumption: Two conceptual TAD transportation casks, designated as Cask A and Cask B, are assumed to have a cylindrical geometry and materials specified in Tables 1 and 2, respectively. The casks are basically constructed of an inner layer of SS 316 for gamma shielding, a middle layer of 5%-borated polyethylene for neutron shielding, and a thin outer layer of SS 316, which serves a structural function as well as shielding secondary gamma rays.

Both Cask A and Cask B have a cavity height of 537.85 cm (211.75 in.) and a cavity diameter of 168.91 cm (66.50 in.). However, Cask A has a total height of 610.845 cm (240.49 in.) and an outside diameter of 267.97 cm (105.50 in.) while the total height and outside diameter of Cask B are 588.85 cm (231.83 in.) and 247.65 cm (97.50), respectively.

Cask A will provide shielding to meet the exterior radiation standards of 10 CFR 71.47(b) (Reference 2.3.1) when loaded with a TAD canister carrying the maximum PWR spent nuclear fuel (SNF). Cask B will satisfy the same radiation standards when loaded with a TAD canister carrying the average PWR SNF.

Table 1. Geometry and Materials of Conceptual TAD Transportation Cask A

Component	Dimension		Material
	(cm)	(in.)	
Total Height	610.85	240.49	N/A
Outside Diameter	267.97	105.50	N/A
Cask Cavity Height	537.85	211.75	N/A
Cask Cavity Diameter (Radius)	168.91 (84.46)	66.50 (33.25)	N/A
Radial Gamma Shield Thickness (Radius)[a]	33.02 (117.48)[a]	13.00 (46.25)[a]	SS 316
Radial Neutron Shield Thickness (Radius)[b]	15.24 (132.72)[b]	6.00 (52.25)[b]	5%-borated polyethylene
Radial Outer Shell Thickness (Radius)[c]	1.27 (133.99)[c]	0.50 (52.75)[c]	SS 316
Top Gamma Shield Thickness (Axial Position)[d]	6.00 (543.85)[d]	2.36 (214.11)[d]	SS 316
Top Neutron Shield Thickness (Axial Position)[d]	10.00 (553.85)[d]	3.94 (218.05)[d]	5%-borated polyethylene
Top Outer Shell Thickness (Axial Position)[d]	2.00 (555.85)[d]	0.79 (218.84)[d]	SS 316
Bottom Gamma Shield Thickness (Axial Position)[d]	35.365 (-36.0)[d]	13.92 (-14.17)[d]	SS 316
Bottom Neutron Shield Thickness (Axial Position)[d]	15 (-51.0)[d]	5.91 (-20.08)[d]	5%-borated polyethylene
Bottom Outer Shell Thickness (Axial Position)[d]	4 (-55.0)[d]	1.57 (-21.65)[d]	SS 316

[a]117.48 = 33.02 + 84.46 and 46.25 = 13.00 + 33.25.
[b]132.72 = 15.24 + 117.48 and 52.25 = 6.00 + 46.25.
[c]133.99 = 1.27 + 132.72 and 52.75 = 0.50 + 52.25.
[d]Coordinate relative to the bottom of the fuel assembly as modeled in MCNP5.

Table 2. Geometry and Materials of Conceptual TAD Transportation Cask B

Component	Dimension		Material
	(cm)	(in.)	
Total Height	588.85	231.83	N/A
Outside Diameter	247.65	97.50	N/A
Cask Cavity Height	537.85	211.75	N/A
Cask Cavity Diameter (Radius)	168.91 (84.46)	66.50 (33.25)	N/A
Radial Gamma Shield Thickness (Radius)[a]	25.4 (109.86)[a]	10.00 (43.25)[a]	SS 316
Radial Neutron Shield Thickness (Radius)[b]	12.7 (122.56)[b]	5.00 (48.25)[b]	5%-borated polyethylene
Radial Outer Shell Thickness (Radius)[c]	1.27 (123.83)[c]	0.50 (48.75)[c]	SS 316
Top Gamma Shield Thickness (Axial Position)[d]	8 (545.85)[d]	3.15 (214.90)[d]	SS 316
Top Neutron Shield Thickness (Axial Position)[d]	None	None	N/A
Top Outer Shell Thickness (Axial Position)[d]	None	None	N/A
Bottom Gamma Shield Thickness (Axial Position)[d]	38.37 (-39.0)[d]	15.10 (-15.35)[d]	SS 316
Bottom Neutron Shield Thickness (Axial Position)[d]	3.00 (-42.0)[d]	1.18 (-16.54)[d]	5%-borated polyethylene
Bottom Outer Shell Thickness (Axial Position)[d]	1.00 (-43.0)[d]	0.39 (-16.93)[d]	SS 316

[a]109.86 = 25.4 + 84.46 and 43.25 = 10.00 + 33.25.
[b]122.56= 12.7 + 109.86 and 48.25 = 5.00+ 43.25.
[c]123.83 = 1.27 + 122.56 and 48.75 = 0.50 + 48.25.
[d]Coordinate relative to the bottom of the fuel assembly as modeled in MCNP5.

Rationale: Currently, a design for the TAD transportation cask does not exist. The casks assumed for this calculation are solely for estimation of the dose reduction due to different source terms. This is a conceptual representation only used in this calculation to estimate the parameters of interest.

Usage: This assumption is used in Sections 6.1 and 6.2.2.

3.2.4 Usage of Unirradiated Fuel for Commercial SNF

Assumption: It is assumed that the active fuel region of the commercial SNF assembly contains the same isotopic concentrations as the fresh, unirradiated fuel, and that the concentrations of fresh fuel with 5% initial enrichment corresponding to maximum SNF are used for all other SNFs.

Rationale: This assumption is a standard practice for shielding calculations throughout the industry accepted by the U. S. Nuclear Regulatory Commission (NRC) (Reference 2.2.28, Table 5.3-5). It should be noted that this assumption applies to material composition only; it does not apply to source terms, which are based on the characteristics of spent fuel.

Usage: This assumption is used in Sections 6.2.4 and 6.2.6.

3.2.5 Homogenization of Radiation Source Regions

Assumption: It is assumed that a commercial SNF assembly consists of four distinct regions (active fuel, bottom end-fitting, plenum, and top end-fitting). The materials and radiation sources of each assembly region are homogenized inside a volume defined by the TAD cavity radius and region height.

Rationale: The assembly representation is consistent with the industry practice for shielding calculations accepted by NRC (Reference 2.2.28, Figure 5.3-6). The effect of source homogenization is twofold: (1) it decreases the mass density of the source region and (2) it places source points slightly closer to detector locations, thus reducing radiation attenuation. The results of *Calculation of the Effect of Source Geometry on the 21-PWR WP Dose Rates* (Reference 2.2.18, pp. 22-26) indicate that the effect of assembly homogenization gives nearly the same or conservative dose rates as the explicit fuel assembly model.

Usage: This assumption is used in Section 6.2.4.

3.2.6 Ignoring Internal Fuel Basket Materials

Assumption: It is assumed that the internal fuel basket materials are ignored.

Rationale: Inclusion of fuel basket materials in the smeared material composition would increase the overall density and, consequently, increase the attenuation of the radiation. Therefore, this assumption is conservative.

Usage: This assumption is used in Sections 6.2.1, 6.2.4 and 6.2.6.

4. METHODOLOGY

4.1 QUALITY ASSURANCE

This calculation was prepared in accordance with EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Reference 2.1.2). The results of this calculation provides worker dose assessment adjustments and this will identify radiological hazards for facilities important to safety. Therefore, the approved version is designated as QA: QA.

4.2 USE OF COMPUTER SOFTWARE

4.2.1 Baseline Software

The Monte Carlo N-Particle computer program (MCNP5) version 1.40 (Reference 2.2.25) is used to calculate the dose rates (neutron, primary gamma and secondary gamma) at various locations around a transportation cask and an aging overpack.

The software specifications are as follows:

- Program Name: MCNP5
- Version/Revision Number: Version 1.40
- Operating Systems: Windows XP
- Software Tracking Number: 11199-1.40-00
- Computer Type: Dell OPTIPLEX GX620

MCNP5, which is Level 1 software, is: (a) appropriate for three-dimensional neutron, gamma, and coupled neutron/gamma shielding calculations, (b) used within the range of validation as documented in *Software Validation Report for: MCNP5 v1.40* (Reference 2.2.21) and (c) obtained from Software Configuration Management and qualified in accordance with procedure IT-PRO-0012, *Qualification of Software* (Reference 2.1.3). Therefore, MCNP5 code is suitable for use in this design calculation. All MCNP5 input and output files documented in this calculation are provided on a compact disc (CD) as Attachment II.

All MCNP cases are executed on one of the following Q computers: QNW-004184, QNW-004187, QNW-004194, and QNW-004196 as shown in the output files.

4.2.2 Commercial off the Shelf Software

The Excel software is used to calculate various input values (i.e., atom densities, weight percentages, geometrical dimensions, normalized source spectra and probabilities, etc). Standard functions of Excel are also used in this design calculation to display results (i.e., gamma and neutron dose rates) in tabular and graphic forms and to perform relative error calculations.

The software specifications are as follows:

- Program Name: Excel
- Version/Revision Number: Microsoft® Excel 2003

- This software is installed on a personal computer running Microsoft Windows XP (central processing unit number 151834)

The user defined formulas, inputs, results, and graphical representations have been verified by hand calculations or visual inspection, and are documented in sufficient detail to allow an independent repetition of the computations. Calculations were verified by hand and graphical representations were found accurate by visual inspection.

Per *Software Management*, Microsoft® Excel is not required to be qualified due to its commercial availability status (Reference 2.1.1, Attachment 4, p. 55, bullet 2).

4.3 CALCULATION APPROACH

This calculation employs the qualified software MCNP5 version 1.40 (Reference 2.2.25), a three-dimensional Monte Carlo code, for performing neutron and coupled neutron-gamma calculations, to estimate dose rates at selected locations on and surrounding a conceptual transportation cask containing a loaded TAD canister.

4.3.1 MCNP5 Program

MCNP5, a general Monte Carlo particle transport code, simulates particle transport through a three-dimensional representation of the nuclear system being analyzed. During the random walk of particles through the system described by the geometry, the code collects information about various events (surface crossing, collisions, track length, etc.) and estimates fluxes in various geometric configurations specified as tallies by the user. It also estimates the statistical precision of the results in the form of relative errors (Reference 2.2.24, pp. 1-2 to 1-8).

Per *Project Design Criteria Document* (Reference 2.2.11, Section 4.10.1.5), the flux estimates are converted to dose rates using the American Nuclear Society (ANS) flux-to-dose rate conversion factors for gammas and neutrons (Reference 2.2.1). The simple variance reduction techniques of Geometry Splitting/Russian Roulette and source probability biasing (Sections 6.3.1 and 6.3.3) are used to enhance computational efficiency.

5. LIST OF ATTACHMENTS

		Number of Pages
Attachment I.	List of Electronic Files on the CD	3
Attachment II.	Compact Disc	N/A

6. CALCULATIONS

This section provides information necessary to perform the calculations in this document. Section 6.1 describes the configurations, the type of CSNF to be analyzed, the number of MCNP runs, and the locations where dose rates are calculated. Section 6.2 provides the calculation input that includes the details of the geometry model, radiation source terms, and material compositions. Input specific to MCNP, dose-rate conversion factors and relative error calculation are described in the later sections.

6.1 DESCRIPTION OF CALCULATIONS

Dose rate calculations are performed with the MCNP5 version 1.40 computer code (Reference 2.2.25). Two conceptual transportation casks, Cask A and Cask B (Assumption 3.2.3), are employed. Each cask contains a TAD canister that is loaded with 21 identical PWR SNF assemblies. Three PWR source terms are analyzed; they are the source terms corresponding to the maximum, design basis, and average PWR SNFs. The characteristics of the PWR source terms are presented in Section 6.2.7. Each PWR source term has neutron and gamma radiation sources that require separate MCNP5 runs. For each radiation source, an axial profile source and a uniform source for the active fuel region are considered. The uniform source for the active fuel region is included in this calculation because this approach was used in combination with source peaking factors in certain calculations (Reference 2.2.16, Sections 3.7 and 3.9 and Reference 2.2.17, Section 5.2.4.2).

The total number of MCNP5 runs is 24, which results from a combination of two conceptual casks, three PWR source terms, two radiation sources, and two axial source distributions for the active fuel region. These 24 runs are categorized into four calculation sets. Each calculation set consists of six runs that is a combination of three PWR source terms and two radiation sources. The characteristics of each calculation set are as follows:

1. Cask A with axial profile sources in the active fuel region,

2. Cask A with uniform axial sources in the active fuel region,

3. Cask B with axial profile sources in the active fuel region,

4. Cask B with uniform axial sources in the active fuel region.

For each MCNP5 run, dose rates are calculated at the exterior surfaces and at distances 1 and 2 meters from the exterior surfaces. Surface tallies and detector tallies (ring and point detectors) as indicated in Figure 1 are employed in all runs. Figure 1 is used to illustrate the deployment of the surface and detector tallies relative to the source regions, and it should not be interpreted as an exact geometry of any particular run. Surface tallies are deployed at all three distances, while ring and point detectors are used only at 1 m and 2 m and not at the cask surfaces. Using point detectors near a surface or in any scattering media is not recommended because very large scores can occur from collisions close (less than a few centimeters) to the point detectors that can lead to results with high relative errors, thus making the calculation difficult to obtain reliable answers.

For the radial direction, surface tallies at the three distances (contact, 1 m and 2 m) are computed for three surface segments (cylindrical rings) between the planes at Z = 145, 175, 205, and 235 cm. The geometric locations of the segments are shown in Figure 1. The axial locations of these segments correspond to the middle of the active fuel region of the PWR SNF assemblies. The average dose rates for each of the segments are calculated for the outside surface and surfaces at 1 m and 2 m from the cask surface. Two ring detectors (instead of point detectors) are deployed at 1 m and 2 m for the radial direction. Ring detectors, instead of point detectors, are used in order to capitalize on the symmetry around the cask axis, thus improving the efficiency of the calculations.

In the axial direction, the average dose rates within three concentric radial surfaces defined by radii of 40, 80, and 120 cm (shown in Figure 1) are calculated for the top and bottom surfaces and at distances 1 m and 2 m from these surfaces. Finally, point detectors at 1 m and 2 m from the top and bottom axial surfaces are employed.

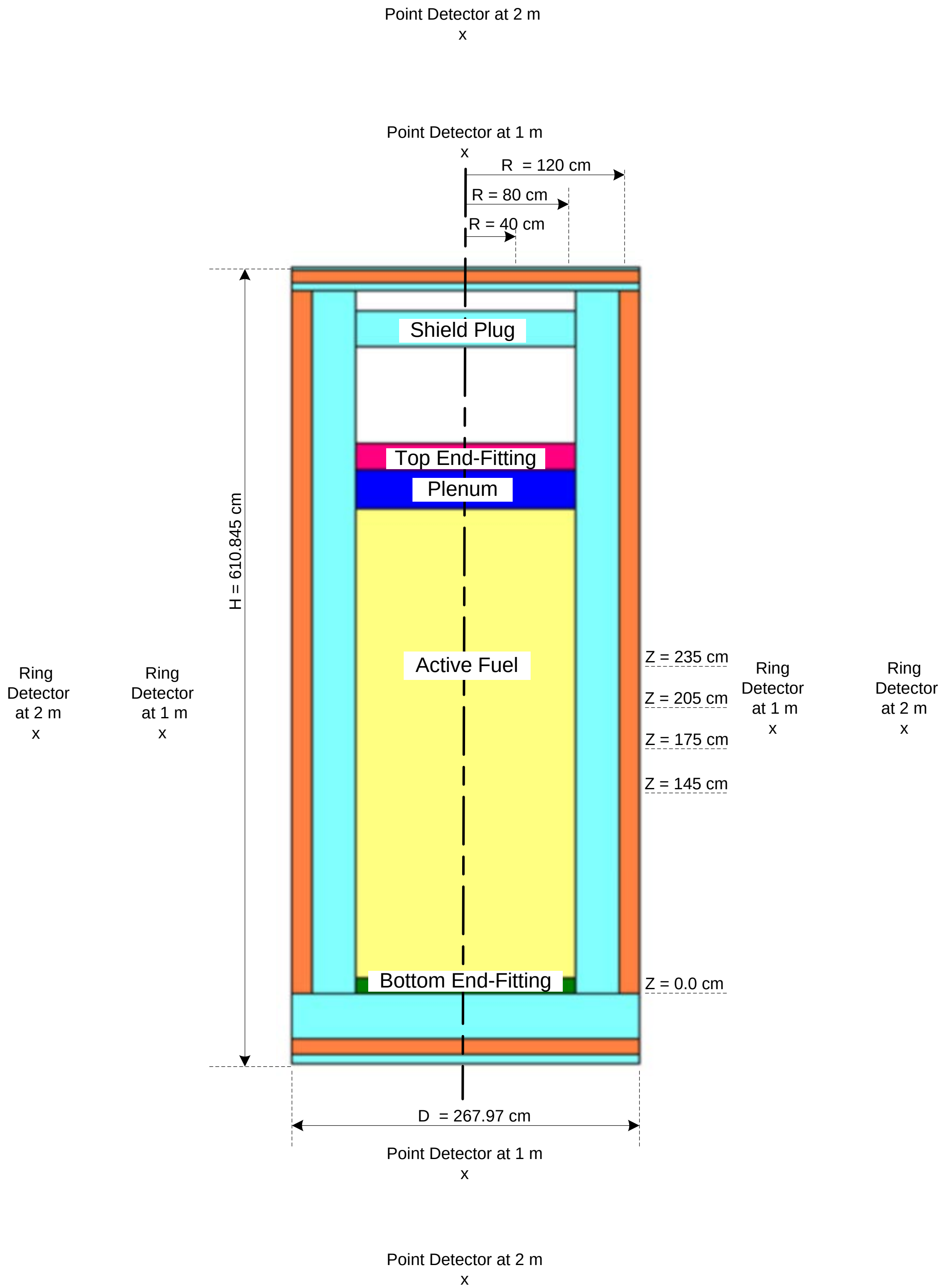

Figure 1. Geometry and Tally Scheme for the TAD Transportation Cask

6.2 CALCULATION INPUT

Technical product input and sources of the input used in the development of this calculation are documented in this section. Tables in this document and in the associated Microsoft® Excel spreadsheets referenced may present numerical values with many significant figures; these values are not to be considered as high precision values since the significant figures are results of calculated values and/or unit conversions.

6.2.1 TAD Canister

The TAD canister will contain either 21 PWR or 44 BWR (boiling water reactor) SNF assemblies (Reference 2.2.22, Section 3.2.1). While the canister design is identical for both PWR and BWR SNF assemblies, the internal basket structure is different depending on the SNF assemblies. However, the internal basket structure material is not included in the calculation model (Assumption 3.2.6).

The TAD canister is a right-circular cylinder with a diameter of 66.5 in. and a height between 186 and 212 in. (Reference 2.2.22, Section 3.2.1). The average and maximum total dose rates on the top surface of a loaded TAD canister must not exceed 800 and 1000 mrem/hr, respectively (Reference 2.2.22, Section 3.1.4). The TAD canister used in this calculation is made of SS 316 with a radial wall and bottom thickness of 0.25 in. (Assumption 3.2.1). The top of the canister has a shield plug that is 11 in. thick SS 316 (Assumption 3.2.2). A thick shield plug is needed to keep the maximum contact dose rate of the top surface below 1000 mrem/hr. The overall dimensions of the TAD canister are provided in Table 3.

Table 3. Dimensions of TAD Canister

Component	Dimension	
	(in.)	(cm)
Maximum height[a]	212	538.48
Outer diameter[a]	66.5	168.91
Thickness of bottom lid[b]	0.25	0.635
Shell thickness[b]	0.25	0.635
Lifting Feature[c]	6	15.24
Height without Lifting Feature	206	523.24
Thickness of shield plug[d]	11.0	27.94

[a]Reference 2.2.22, Section 3.1.1; [b]Assumption 3.2.1; [c]Reference 2.2.22, p. Attachment C-1; [d]Assumption 3.2.2.

6.2.2 Conceptual TAD Transportation Casks

Two conceptual TAD transportation casks, designated as Cask A and Cask B, are employed in this calculation (Assumption 3.2.3). They both have a cylindrical geometry with dimensions and materials specified in Tables 1 and 2 of Section 3.2.3. Cask A will provide shielding to meet the exterior radiation standards of 10 CFR 71.47(b) (Reference 2.3.1) when loaded with a TAD canister carrying the maximum PWR SNF. Cask B will satisfy the same radiation standards when loaded with a TAD canister carrying the average PWR SNF. The reason to analyze both Casks A and B is to cover a broad range of characteristics of the CSNF.

The cavity dimensions of the conceptual casks are: 537.85 cm (211.75 in.) in height and 168.91 cm (66.5 in.) in diameter (Tables 1 and 2). This cavity will accommodate the TAD canister described in Table 3 without the lifting feature. This is the geometry model used in the MCNP5 calculations.

6.2.3 Fuel Assembly Selection

PWR and BWR Source Term Sensitivity Study (Reference 2.2.11, Tables 71 through 84) shows that the source terms generated for the B&W 15x15 Mark B fuel assembly with 475 kg uranium loading bound the source terms of other PWR assembly types; therefore, this assembly type is selected as the representative PWR fuel assembly. The gamma and neutron source terms for the B&W 15x15 Mark B assembly are generated in *PWR Source Term Generation and Evaluation* (Reference 2.2.9), and are used in this calculation.

6.2.4 B&W 15x15 Mark B PWR Fuel Assembly

B&W 15x15 Mark B fuel assembly consists of four regions: top end-fitting, plenum, active fuel, and bottom end-fitting. The materials and radiation sources of each assembly region are homogenized inside a volume defined by the region height and the interior diameter of the TAD canister (Assumption 3.2.5). The active fuel region is homogenized with fresh, unirradiated fuel (Assumption 3.2.4). Since the internal structure (i.e. basket) design of the TAD is currently not finalized, the composition of the homogenized fuel does not include the basket materials (Assumption 3.2.6) and therefore does not take credit for any shielding that these materials may provide.

Table 4 provides the design parameters for the B&W 15x15 Mark B fuel assembly. Data provided here are used in Attachment II, *PWR_fuel comp.xls*, worksheet *B&Wassy*.

Table 4. B&W 15x15 Mark B Fuel Assembly Description

Component	Material	Characteristic	Value	Specific Reference
Assembly	N/A	Array Size	15 x 15	Reference 2.2.27, Table 2-2
		Fuel Pins / Assembly	208	
		Guide Tubes / Assembly	16	
		Instrument Tubes / Assembly	1	
		Pin Pellet Diameter	0.936244 cm (0.3686 in.)	Reference 2.2.20, p. 2A-34
		Pin Pitch	1.44272 cm (0.568 in.)	Reference 2.2.27, Table 2-2
		Active Fuel Height	360.172 cm (141.8 in.)	
		Assembly Width	21.68144 cm (8.536 in)	Reference 2.2.20, p. 2A-31
		Assembly Height	420.6875 cm (165.625 in.)	
		Mass U / assembly	463.63 kg	
Guide tube	Zircaloy-4	Outer Diameter	1.3462 cm (0.53 in.)	Reference 2.2.27, Table 2-2
		Inner Diameter	1.26492 cm (0.498 in.)	
Instrument tube	Zircaloy-4	Outer Diameter	1.38193 cm (0.5441 in.)	
		Inner Diameter	1.12014 cm (0.441 in.)	
Cladding`	Zircaloy-4	Inner Diameter	0.95758 cm (0.377 in.)	
		Outer Diameter	1.0922 cm (0.43 in.)	
Plenum region	N/A	Length	29.7688 cm (11.720 in.).	Reference 2.2.20, p. 2A-34
Top nozzle	SS CF3M	Mass/Assembly (Top)	7.48 kg	Reference 2.2.20, p. 2A-32
Bottom nozzle	SS CF3M	Mass/Assembly (Bottom)	8.16 kg	
Guide tubes	Zircaloy-4	Mass/Assembly (in Core)	8.0 kg	
Instrument tube	Zircaloy-4	Mass/Assembly (in Core)	0.64 kg	
Spacer-plenum	Inconel-718	Mass/Assembly (Plenum)	1.04 kg	
Spacer-bottom	Inconel-718	Mass/Assembly (Bottom)	1.3 kg	
Spacer-in core	Inconel-718	Mass/Assembly (in Core)	4.9 kg	
Spring retainer	SS CF3M	Mass/Assembly (Top)	0.91 kg	
Holddown spring	Inconel-718	Mass/Assembly (Top)	1.8 kg	
Upper end plug	SS 304	Mass/Assembly (Top)	0.06 kg	
Upper nut	SS 304L	Mass/Assembly (Top)	0.51 kg	
Lower nut	SS 304	Mass/Assembly (Bottom)	0.15 kg	
Grid supports	Zircaloy-4	Mass/Assembly (in Core)	0.64 kg	
Plenum spring	SS 302	Mass/Assembly (Plenum)	0.042 lb (0.01905 kg)	Reference 2.2.20, p. 2A-34

Note: Some data in this table are given in British units in the references; these data are converted into metric units as the inputs to MCNP5 are in metric units.

The assembly region heights, as modeled in MCNP, are presented in Table 5 utilizing values from Table 4. Table 5 is taken from *Dose Rate Calculation for Exhaust Main Drifts* (Reference 2.2.13, Table 3).

Table 5. PWR Fuel Assembly Regions

Component	Height	Reference
Plenum	29.7688 cm (11.720 in.)	Reference 2.2.20, p. 2A-34
Active Fuel	360.172 cm (141.8 in.)	Table 3
Bottom End-Fitting	10.77 cm (4.24 in.)	Calculated[a]
Top End-Fitting	19.98 cm (7.87 in.)	Calculated[b]

Source: Reference 2.2.13, Table 3.

[a]Calculated based on data Reference 2.2.27, Figures 2-3 and 2-7 (Region 9 Height [16.723 cm] + Region 10 Height [5.08 cm] – Lower Fuel Plenum and End Cap [11.033 cm]).

[b]Calculated (Assembly Length – Active Fuel Length – Plenum Length – Bottom End-fitting Length).

6.2.5 Material Compositions

The TAD transportation cask component material specifications are defined in Table 1. The TAD canister is constructed of SS 316 (Assumption 3.2.1). The PWR fuel assembly materials used to homogenize the fuel regions are defined in Table 4. Table 6 contains the material compositions defining the TAD canister, WP, and fuel assemblies.

Table 6. Chemical Compositions of Materials

Material	Density (g/cc)	Isotopic Weight Percent	Reference
SS 302	N/A	C: 0.150 Mn: 2.000 P: 0.045 S: 0.030 Si: 0.750 Cr: 18.000 Ni: 9.000 N: 0.100 Fe: 69.925	Attachment II, *PWR_fuel comp.xls,* worksheet *ferrous* Reference 2.2.2, SEC II A SA-240, Table 1 for SS 302, SS 304, and SS 304L Reference 2.2.2, SEC II A SA-351/SA-351M, Table 2 for SS CF3M
SS 304	N/A	C: 0.080 Mn: 2.000 P: 0.045 S: 0.030 Si: 0.750 Cr: 19.000 Ni: 9.250 N: 0.100 Fe: 68.745	
SS 304L	N/A	C: 0.03 Mn: 2.000 P: 0.045 S: 0.030 Si: 0.750 Cr: 19.000 Ni: 10.000 N: 0.100 Fe: 68.045	
SS CF3M	N/A	C: 0.030 Mn: 1.500 P: 0.040 S: 0.040 Si: 1.500 Cr: 19.000 Ni: 11.000 Mo: 2.500 Fe: 64.390	
Inconel 718	N/A	C: 0.080 Mn: 0.350 Si: 0.350 Cr: 19.000 Ni: 52.500 Co: 1.000 Mo: 3.050 Fe: 16.809 Nb: 5.125 Ti: 0.900 Al: 0.500 Cu: 0.300 S: 0.015 P: 0.015 B: 0.006	Attachment II, *PWR_fuel comp.xls,* worksheet *alloys* [a]Reference 2.2.3, p. 666, Table 6 Reference 2.2.2, SEC II B SB-637, Table 1 for Inconel 718 Reference 2.2.4, Table 2 for Zircaloy 4
Zircaloy 4	6.56[a]	Cr: 0.100 Fe: 0.210 O: 0.125 Sn: 1.450 Zr: 98.115	
SS 316	7.98[b]	C: 0.080 Mn: 2.000 P: 0.045 S: 0.030 Si: 0.750 Cr: 17.000 Ni: 12.000 Mo: 2.500 N: 0.100 Fe: 65.495	Attachment II, *PWR_fuel comp.xls,* worksheet *others* Reference 2.2.2, SEC II A SA-240, Table 1 for SS 316 [b]Reference 2.2.5, Table X1

6.2.6 Homogenization Assembly Materials

The atom density of an element or isotope, in *atoms/b·cm*, in a homogenized region is calculated according to the following equation (Reference 2.2.23, Appendix B):

$$N_i = \frac{M_i \times N_{Avogadro}}{A_i \times V \times K} \qquad \text{Equation 1}$$

where: N_i = Atom density of element/isotope i (*atoms/b·cm*)

M_i = Mass of element/isotope i (g)

$N_{Avogadro}$ = Avogadro's constant, 0.6022 x 10^{24} (*atoms/mole*)

A_i = Atomic weight of element/isotope i ($g/mole$)
V = Homogenization volume (cm^3)
K = Unit transformation constant = 10^{24} ($b \cdot cm/cm^3$)

Equation 1 is used in Attachment II, spreadsheet *PWR_fuel comp.xls*, worksheet *B&Wassy* to calculate the atom densities for various elements and isotopes. The mass of elements/isotopes and Avogadro's constant are provided in Reference 2.2.26.

Table 7 lists the composition of the homogenized assembly regions (active fuel, plenum, top end-fitting, and bottom end-fitting) for the PWR assembly. The active fuel region contains fresh, unirradiated fuel (Assumption 3.2.4). Since the internal structure (i.e. basket) design of the TAD is currently not finalized, the composition of either homogenized fuel does not include the basket materials and therefore does not take credit for any shielding that these materials may provide (Assumption 3.2.6).

Table 7. Isotopic Compositions of Homogenized PWR Assembly Regions

Element/ Isotope	Atom Densities for Homogenized Regions *(atoms/b·cm)*			
	Active Fuel	**Bottom End-Fitting**	**Plenum**	**Top End-Fitting**
^{10}B	8.61E-09	7.64E-08	2.21E-08	5.70E-08
^{11}B	3.47E-08	3.07E-07	8.90E-08	2.30E-07
C	5.19E-07	1.60E-05	1.38E-06	9.93E-06
N	--	5.70E-07	2.62E-08	1.17E-06
O	6.21E-03	--	1.42E-05	--
Al	1.44E-06	1.28E-05	3.71E-06	9.57E-06
Si	9.71E-07	2.43E-04	2.59E-06	1.39E-04
P	3.77E-08	6.06E-06	1.02E-07	3.60E-06
S	3.65E-08	5.81E-06	9.71E-08	3.40E-06
Ti	1.47E-06	1.30E-05	3.76E-06	9.71E-06
Cr	3.20E-05	1.87E-03	7.79E-05	1.13E-03
Mn	4.97E-07	1.26E-04	1.41E-06	7.49E-05
Fe	3.03E-05	5.31E-03	7.17E-05	3.13E-03
Co	1.32E-06	1.17E-05	3.40E-06	8.76E-06
Ni	6.97E-05	1.44E-03	1.80E-04	9.40E-04
Cu	3.68E-07	3.27E-06	9.45E-07	2.44E-06
Zr	1.96E-03	--	1.95E-03	--
Nb	4.30E-06	3.82E-05	1.10E-05	2.85E-05
Mo	2.48E-06	1.35E-04	6.36E-06	7.91E-05
Sn	2.23E-05	--	2.22E-05	--
^{234}U	1.39E-06	--	--	--
^{235}U	1.57E-04	--	--	--
^{236}U	7.19E-07	--	--	--
^{238}U	2.94E-03	--	--	--
Total	1.14E-02	9.24E-03	2.35E-03	5.57E-03

Source: Attachment II, spreadsheet *PWR_fuel comp.xls,* worksheet *B&Wassy*.

The isotopic composition of commercially available ^{235}U enriched uranium is determined by the given initial ^{235}U enrichment using the following equations (Reference 2.2.6, p. 20):

$$wt\%^{235}U = {}^{235}U_{enrichment\_of\_the\_associated\_fuel\_batch} \quad \text{Equation 2}$$

$$wt\%^{234}U = 0.007731 \times (wt\%^{235}U)^{1.0837} \quad \text{Equation 3}$$

$$wt\%^{236}U = 0.0046 \times (wt\%^{235}U) \quad \text{Equation 4}$$

$$wt\%^{238}U = 100 - (wt\%^{234}U + wt\%^{235}U + wt\%^{236}U) \quad \text{Equation 5}$$

The weight percentages of uranium isotopes for PWR fuel are calculated in Attachment II, spreadsheet *PWR_fuel comp.xls*, worksheet *B&Wassy*, using Equations 2 through 5.

6.2.7 PWR Source Terms

This calculation uses the following three PWR source terms:

- Maximum source (5.0 wt % initial ^{235}U enrichment, 80 GWd/MTU burnup, and 5-year decay time) (Reference 2.2.9, Section 5.5). Table 8 lists the gamma source terms for the fuel and non-fuel regions and the neutron source term for the fuel region.

- Design Basis source (4.0 wt % initial ^{235}U enrichment, 60 GWd/MTU burnup, and 10-year decay time) (Reference 2.2.8, Section 5.5.2). Table 9 lists the gamma source terms for the fuel and non-fuel regions and the neutron source term for the fuel region.

- Average source (4.0 wt % initial ^{235}U enrichment, 48 GWd/MTU burnup, and 25-year decay time) (Reference 2.2.9, Section 5.5). Table 10 lists the gamma source terms for the fuel and non-fuel regions and the neutron source term for the fuel region.

These sources (i.e. maximum, design basis, and average) are described in this section. For dose rate calculations, all the fuel assemblies in a transportation cask are of the same characteristics. Also, gamma radiation source terms for the PWR assembly are provided for the four assembly regions, while neutron source term is only present in the active fuel region. Gamma radiation sources in the non-active fuel region are distributed uniformly within each source region. Gamma and neutron sources in the active fuel region are modeled as uniform distributions or with axial source profiles.

The PWR gamma and neutron axial source profiles for the active fuel region presented in Table 11 are applied to the active fuel region of all three source terms (i.e., maximum, design basis, and average) when appropriate.

Table 8. Gamma and Neutron Sources for the Maximum PWR SNF Assembly

Gamma Intensity (photons/s)					Neutron Intensity (neutrons/s)	
Upper Energy Boundary (MeV)	**Bottom End-Fitting Region[a]**	**Active Fuel Region[b]**	**Plenum Fuel Region[c]**	**Top End-Fitting Region[d]**	**Upper Energy Boundary (MeV)**	**Active Fuel Region[b]**
5.00E-02	5.94E+11	2.33E+15	5.28E+11	3.79E+11	1.00E-01	0.00E+00
1.00E-01	1.16E+11	6.44E+14	6.09E+10	7.43E+10	4.00E-01	8.05E+07
2.00E-01	2.83E+10	5.22E+14	3.52E+10	1.79E+10	9.00E-01	4.11E+08
3.00E-01	1.41E+09	1.48E+14	1.96E+09	8.91E+08	1.40E+00	3.76E+08
4.00E-01	1.90E+09	9.85E+13	5.86E+09	1.17E+09	1.85E+00	2.76E+08
6.00E-01	1.91E+09	1.53E+15	1.10E+11	7.41E+07	3.00E+00	4.85E+08
8.00E-01	4.35E+09	4.70E+15	5.95E+10	2.37E+09	6.43E+00	4.43E+08
1.00E+00	1.37E+11	7.08E+14	8.03E+09	7.66E+10	2.00E+01	3.93E+07
1.33E+00	3.38E+13	4.55E+14	1.74E+13	2.17E+13	Total	2.11E+09
1.66E+00	9.53E+12	1.30E+14	4.91E+12	6.12E+12	--	
2.00E+00	1.87E+03	1.44E+12	9.19E+02	1.13E+03		
2.50E+00	2.26E+08	2.49E+12	1.16E+08	1.45E+08		
3.00E+00	3.51E+05	1.10E+11	1.81E+05	2.25E+05		
4.00E+00	7.66E-08	1.39E+10	1.00E-08	4.16E-08		
5.00E+00	0.00E+00	7.09E+07	0.00E+00	0.00E+00		
6.50E+00	0.00E+00	2.86E+07	0.00E+00	0.00E+00		
8.00E+00	0.00E+00	5.58E+06	0.00E+00	0.00E+00		
1.00E+01	0.00E+00	1.19E+06	0.00E+00	0.00E+00		
Total	4.42E+13	1.13E+16	2.31E+13	2.84E+13		

Source: Reference 2.2.9, Attachment X, (compact disc) [a]*Waste.Stream.E2.R2.B14.cut;* [b]*Waste.Stream.E2.R1.B14.cut;* [c]*Waste.Stream.E2.R3.B14.cut;* [d]*Waste.Stream.E2.R4.B14.cut.*

Table 9. Gamma and Neutron Sources for the Design Basis PWR SNF Assembly

Gamma Intensity (photons/s)					Neutron Intensity (neutrons/s)	
Upper Energy Boundary (MeV)	**Bottom End-Fitting Region[a]**	**Active Fuel Region[b]**	**Plenum Fuel Region[c]**	**Top End-Fitting Region[d]**	**Upper Energy Boundary (MeV)**	**Active Fuel Region[b]**
5.00E-02	2.73E+11	1.21E+15	1.88E+11	1.75E+11	1.00E-01	0.00E+00
1.00E-01	5.28E+10	3.29E+14	2.77E+10	3.39E+10	4.00E-01	3.16E+07
2.00E-01	1.28E+10	2.45E+14	1.17E+10	8.19E+09	9.00E-01	1.61E+08
3.00E-01	6.39E+08	7.13E+13	6.33E+08	4.07E+08	1.40E+00	1.48E+08
4.00E-01	8.50E+08	4.55E+13	1.64E+09	5.33E+08	1.85E+00	1.09E+08
6.00E-01	4.92E+08	2.26E+14	2.69E+10	3.37E+07	3.00E+00	1.91E+08
8.00E-01	2.91E+09	2.37E+15	1.60E+10	1.86E+09	6.43E+00	1.74E+08
1.00E+00	5.40E+09	1.22E+14	2.48E+09	3.41E+09	2.00E+01	1.54E+07
1.33E+00	1.54E+13	1.95E+14	7.97E+12	9.90E+12	Total	8.30E+08
1.66E+00	4.35E+12	4.50E+13	2.25E+12	2.80E+12	--	
2.00E+00	2.35E+00	1.52E+11	1.49E+02	2.15E-02		
2.50E+00	1.03E+08	5.17E+10	5.34E+07	6.64E+07		
3.00E+00	1.60E+05	3.79E+09	8.29E+04	1.03E+05		
4.00E+00	9.43E-10	4.97E+08	1.55E-10	5.19E-10		
5.00E+00	0.00E+00	2.82E+07	0.00E+00	0.00E+00		
6.50E+00	0.00E+00	1.13E+07	0.00E+00	0.00E+00		
8.00E+00	0.00E+00	2.22E+06	0.00E+00	0.00E+00		
1.00E+01	0.00E+00	4.71E+05	0.00E+00	0.00E+00		
Total	2.01E+13	4.86E+15	1.05E+13	1.29E+13		

Source: Reference 2.2.9, Attachment X, (compact disc) [a]*Waste.Stream.E5.R2.B11.cut;* [b]*Waste.Stream.E5.R1.B11.cut;* [c]*Waste.Stream.E5.R3.B11.cut;* [d]*Waste.Stream.E5.R4.B11.cut.*

Table 10. Gamma and Neutron Sources for the Average PWR SNF Assembly

Gamma Intensity (photons/s)					Neutron Intensity (neutrons/s)	
Upper Energy Boundary (MeV)	**Bottom End-Fitting Region[a]**	**Active Fuel Region[b]**	**Plenum Fuel Region[c]**	**Top End-Fitting Region[d]**	**Upper Energy Boundary (MeV)**	**Active Fuel Region[b]**
5.00E-02	3.36E+10	6.70E+14	1.86E+10	2.17E+10	1.00E-01	0.0000E+00
1.00E-01	6.02E+09	1.99E+14	3.14E+09	3.87E+09	4.00E-01	7.48E+06
2.00E-01	1.46E+09	1.26E+14	8.53E+08	9.36E+08	9.00E-01	3.82E+07
3.00E-01	7.30E+07	3.89E+13	4.39E+07	4.69E+07	1.40E+00	3.52E+07
4.00E-01	9.47E+07	2.63E+13	7.16E+07	6.07E+07	1.85E+00	2.61E+07
6.00E-01	1.41E+07	2.05E+13	5.04E+08	3.83E+06	3.00E+00	4.69E+07
8.00E-01	2.08E+09	1.24E+15	1.92E+09	1.44E+09	6.43E+00	4.18E+07
1.00E+00	2.08E+09	1.10E+13	1.64E+09	1.44E+09	2.00E+01	3.65E+06
1.33E+00	1.75E+12	2.95E+13	9.09E+11	1.12E+12	Total	1.99E+08
1.66E+00	4.94E+11	5.13E+12	2.57E+11	3.18E+11	--	
2.00E+00	9.73E-01	6.75E+10	6.14E+01	8.72E-03		
2.50E+00	1.17E+07	3.53E+09	6.09E+06	7.54E+06		
3.00E+00	1.82E+04	2.88E+08	9.44E+03	1.17E+04		
4.00E+00	1.86E-11	1.98E+07	1.49E-11	1.27E-11		
5.00E+00	0.00E+00	6.69E+06	0.00E+00	0.00E+00		
6.50E+00	0.00E+00	2.69E+06	0.00E+00	0.00E+00		
8.00E+00	0.00E+00	5.27E+05	0.00E+00	0.00E+00		
1.00E+01	0.00E+00	1.12E+05	0.00E+00	0.00E+00		
Total	2.29E+12	2.37E+15	1.19E+12	1.47E+12		

Source: Reference 2.2.9, Attachment X, (compact disc) [a]*Waste.Stream.E5.R2.B9.cut;* [b]*Waste.Stream.E5.R1.B9.cut;* [c]*Waste.Stream.E5.R3.B9.cut;* [d]*Waste.Stream.E5.R4.B9.cut.*

Table 11. Gamma and Neutron Axial Source Profiles for a PWR Assembly

Axial boundaries (From midplane) *(cm)*	**TOP**		**BOTTOM**	
	Neutron	**Gamma**	**Neutron**	**Gamma**
0.00	1.554	1.117	1.554	1.117
11.43	1.537	1.114	1.571	1.120
22.86	1.521	1.111	1.588	1.123
34.29	1.504	1.108	1.605	1.126
45.72	1.486	1.104	1.622	1.129
57.15	1.464	1.100	1.636	1.131
68.58	1.438	1.095	1.648	1.133
80.01	1.401	1.088	1.657	1.135
91.44	1.350	1.078	1.654	1.134
102.87	1.277	1.063	1.625	1.129
114.30	1.165	1.039	1.554	1.117
125.73	0.998	0.9995	1.414	1.091
137.16	0.769	0.9365	1.172	1.041
148.59	0.492	0.8375	0.816	0.951
160.02	0.220	0.6850	0.402	0.797
171.45	0.046	0.4625	0.092	0.551
182.88	0.0	0.0	0.0	0.0

Source: Reference 2.2.19, Table S4.4.5.

6.3 MCNP SPECIFIC INPUT

6.3.1 Source Probability

A linear radial distribution is used for all gamma and neutron sources. The linear radial distribution is sampled using the built-in power function $p(x) = c \cdot x^a$ with $a = 1$ for the radial direction. This sampling method results in a uniform source distribution over the area bounded by the outer radius of the source.

The source axial distributions are uniform for all four source regions. The axial uniform distribution is sampled using the built-in power function $p(x) = c \cdot x^a$ with $a = 0$ for extent.

The energy distributions of the gamma and neutron source terms are treated as energy probabilities and are applied in MCNP5 using ***SI/SP*** cards

6.3.2 Dose Rate and Flux Tallies

MCNP5 dose rate calculations feature separate runs for the following calculation types:

- a photon transport calculation for primary gamma contribution to the dose rates from photon fluxes.

- a coupled neutron/photon transport calculation for neutrons and secondary gamma (photons generated by neutron being captured) contributions to dose rates from neutron and gamma fluxes.

The tally type *F2* is used in this design calculation as flux estimators. The type *F2* tally evaluates the flux averaged over a surface in $particles/cm^2/s$.

To generate dose rates in terms of *rem/hr*, the ***FM*** (tally multiplier) and ***DE/DF*** (dose energy/dose conversion factors) cards are used to enter the tally multiplier factor (source intensity in *particles/s*), energy boundaries in *MeV*, and corresponding dose conversion factors in $(rem/hr)/(particles/cm^2/s)$, respectively. These factors were used in the input files.

In order for the *F2* tally to accumulate flux over a surface, a specific surface area is required. The ***SD*** cards are used to enter a surface area in cm^2 over which the flux will be tallied for an *F2* tally.

6.3.3 Variance Reduction Techniques

Variance reduction technique is usually employed in order to increase the efficiency of a calculation and obtain statistically meaningful results within reasonable computer time. In Monte Carlo calculations when variance reduction scheme is employed, the weights of particles are adjusted in order to account for the biasing and to preserve a fair game.

Geometry splitting and Russian roulette techniques described in Reference 2.2.24 (pp. 2-140 – 2-142) are useful in shielding calculations and therefore deployed in all the MCNP5 runs.

As particles migrate in an important direction (toward the detector), they are increased in number to provide better sampling by means of geometry splitting across geometric boundaries. Russian roulette (the reverse process) is played when particles travel in an unimportant direction to allow termination of unimportant histories. The ***IMP*** card, required for every cell card, is used to implement this technique.

The other variance reduction technique deployed in the MCNP5 runs is source intensity biasing for the gamma sources from the four source regions (active fuel, bottom end-fitting, plenum, and top end-fitting). The natural total gamma source intensity of commercial SNF is dominated by the gamma source in the active fuel region. This active fuel gamma source usually accounts for over 95% of the total gamma source intensity. In order to improve the efficiency of the axial dose rate calculations, a biased source probability distribution is employed for the primary gamma dose rate calculations. The biased gamma source probability distribution is chosen to be 0.05, 0.80, 0.10, and 0.05 for the bottom end-fitting, the active fuel, the plenum, and the top end-fitting regions, respectively.

6.4 DOSE CONVERSION FACTORS

Project Design Criteria Document (Reference 2.2.11, Section 4.10.1.5) requires the use of flux-to-dose rate conversion factors from ANSI/ANS-6.1.1-1977 (Reference 2.2.1) for dose rate evaluations. Table 16 lists the neutron and gamma dose conversion factors used in the MCNP5 calculations.

Table 12. Gamma and Neutron Flux to Dose Conversion Factors

Gamma				**Neutron**	
Energy (MeV)	**Conversion Factors** (rem/hr)/(photon/cm^2/s)	**Energy** (MeV)	**Conversion Factors** (rem/hr)/(photon/cm^2/s)	**Energy** (MeV)	**Conversion Factors** (rem/hr)/(photon/cm^2/s)
0.01	3.96E-06	1.40	2.51E-06	2.50E-08	3.67E-06
0.03	5.82E-07	1.80	2.99E-06	1.00E-07	3.67E-06
0.05	2.90E-07	2.20	3.42E-06	1.00E-06	4.46E-06
0.07	2.58E-07	2.60	3.82E-06	1.00E-05	4.54E-06
0.10	2.83E-07	2.80	4.01E-06	1.00E-04	4.18E-06
0.15	3.79E-07	3.25	4.41E-06	1.00E-03	3.76E-06
0.20	5.01E-07	3.75	4.83E-06	1.00E-02	3.56E-06
0.25	6.31E-07	4.25	5.23E-06	1.00E-01	2.17E-05
0.30	7.59E-07	4.75	5.60E-06	5.00E-01	9.26E-05
0.35	8.78E-07	5.00	5.80E-06	1.00E+00	1.32E-04
0.40	9.85E-07	5.25	6.01E-06	2.50E+00	1.25E-04
0.45	1.08E-06	5.75	6.37E-06	5.00E+00	1.56E-04
0.50	1.17E-06	6.25	6.74E-06	7.00E+00	1.47E-04
0.55	1.27E-06	6.75	7.11E-06	1.00E+01	1.47E-04
0.60	1.36E-06	7.50	7.66E-06	1.40E+01	2.08E-04
0.65	1.44E-06	9.00	8.77E-06	2.00E+01	2.27E-04
0.70	1.52E-06	11.00	1.03E-05		
0.80	1.68E-06	13.00	1.18E-05		
1.00	1.98E-06	15.00	1.33E-05		

Source: Reference 2.2.1, Tables 1 and 3.

6.5 RELATIVE ERROR CALCULATION

By definition (Reference 2.2.24, Equation 2.19), the estimated statistic relative error of the *i* component is:

$$R_i = \frac{\sqrt{S_i^2}}{T_i} \qquad \text{Equation 6}$$

where: i = tally component index
R_i = relative error of the *i* component
S^2_i = variance of the *i* component
T_i = tally *i* component

For a result (i.e., dose rate) computed as a sum of different tallies, the statistical relative error of the computed value is obtained from the variance of the result - S^2_{total}, which is the sum of the estimated variances of the individual tallies S^2_i:

$$S^2_{Total} = \sum_{i=1}^{n} S_i^2 \qquad \text{Equation 7}$$

where: S^2_{Total} = total estimated variance
n = total number of components

Therefore, the total tally value (dose rate) and the associated relative error are derived according to Equations 8 and 9.

$$T_{Total} = \sum_{i=1}^{n} T_i \qquad \text{Equation 8}$$

$$R_{Total} = \frac{\sqrt{S^2_{Total}}}{T_{Total}} = \frac{\sqrt{\sum_{i=1}^{n} S_i^2}}{T_{Total}} = \frac{\sqrt{\sum_{i=1}^{n} (R_i \times T_i)^2}}{T_{Total}} \qquad \text{Equation 9}$$

where: R_{Total} = total estimated relative error
T_{Total} = total estimated tally

Equations 8 and 9 are utilized in Attachment II to evaluate total dose rates and their relative errors.

7. RESULTS AND CONCLUSIONS

7.1 RESULTS

The following sections summarize the results of this calculation. Section 7.1.1 presents results for Conceptual Cask A while Section 7.1.2 for Conceptual Cask B. Section 7.1.3 provides comparisons of the dose-rate reduction factors due to the two conceptual casks and the axial source distributions in the active fuel region. Dose rates and relative errors can be found in Attachment II within the output files and Excel files.

7.1.1 Dose Rates of Conceptual Cask A

This section presents dose-rate results of the calculation sets 1 and 2, as described in Section 6.1, for Cask A. Set 1 has axial profile sources in the active fuel region and consist of six runs resulting from the three PWR SNF source terms (maximum, design basis, and average) and the two radiation sources (gammas and neutrons). Set 2 has uniform axial sources in the active fuel region and consists of six runs resulting from the three PWR SNF source terms and the two radiation sources.

As described in Section 6.1, dose rates are calculated at the three exterior surfaces (radial, top, and bottom) and at distances 1 m and 2 m from the exterior surfaces. The total dose rates for set 1 are presented in Tables 13, 14 and 15 for the radial, top, and bottom directions, respectively. However the components (primary gamma, neutron, and secondary gamma) contributing to the total dose rates as well as the relative error calculations can be found in Attachment II Excel file *MCNP-Results1.xls*, worksheets *Maximum, DesignBasis, and Average*. Similarly, the total dose rates for set 2 are shown in Tables 16, 17, and 18. The dose-rate components and the relative errors can be found in Attachment II Excel file *MCNP-Results2.xls*, worksheets *Maximum, DesignBasis, and Average*.

The surface tallies in Tables 13 and 16 are the radial total dose rates for the middle segment (at Z between 175 and 205 cm in Figure 1) at contact, 1 m, and 2 m from the radial surface. The surface tallies in Tables 14 and 17 are the top axial dose rates for the central segment within a 40-cm radius at contact and 1 m and 2 m from the top surface. Similarly, the surface tallies in Tables 15 and 18 are the bottom axial dose rates within a 40-cm radius.

This cask is expected to meet exterior radiation standards of 10 CFR 71.47(b) (Reference 2.3.1) when loaded with a TAD canister carrying the maximum PWR SNF. Based on the results in Tables 13 through 18, it is clear that all cask surface contact dose rates are less than 200 mrem/hr and that all 2-m dose rates are less than 10 mrem/hr. Therefore, conceptual Cask A indeed meets the 10 CFR 71.47(b) dose–rate requirements.

In these 6 tables, the dose-rate reduction factors between the maximum and the design basis fuels, the maximum and the average fuels, and the design basis and the average fuels are also presented.

Table 13. Radial Dose Rates from Conceptual Cask A, Axial Profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	3.20E-02	0.0237	1.16E-02	0.0222	2.62E-03	0.0219	2.75	12.23	4.45
1 m	1.33E-02	0.0164	4.94E-03	0.0171	1.06E-03	0.0162	2.69	12.61	4.68
2 m	7.49E-03	0.0198	2.85E-03	0.0225	5.84E-04	0.0162	2.63	12.82	4.88
Ring Detectors									
1 m	1.33E-02	0.0116	4.92E-03	0.0115	1.08E-03	0.0124	2.71	12.29	4.54
2 m	7.56E-03	0.0118	2.79E-03	0.0110	6.05E-04	0.0128	2.71	12.50	4.62

Source: Attachment II, *MCNP-Results1.xls,* worksheet *Summary.*

Table 14. Top Axial Dose Rates from Conceptual Cask A, Axial Profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	1.42E-02	0.0368	6.28E-03	0.0446	9.34E-04	0.0483	2.26	15.20	6.72
1 m	5.70E-03	0.0289	2.63E-03	0.0426	3.75E-04	0.0381	2.17	15.20	7.01
2 m	2.65E-03	0.0364	1.23E-03	0.0547	1.69E-04	0.0374	2.16	15.75	7.30
Point Detectors									
1 m	5.98E-03	0.0238	2.74E-03	0.0271	4.02E-04	0.0354	2.19	14.89	6.81
2 m	2.73E-03	0.0218	1.23E-03	0.0245	1.80E-04	0.0336	2.21	15.15	6.84

Source: Attachment II, *MCNP-Results1.xls,* worksheet *Summary.*

Table 15. Bottom Axial Dose Rates from Conceptual Cask A, Axial profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	6.53E-03	0.0298	2.65E-03	0.0276	5.10E-04	0.0341	2.47	12.78	5.18
1 m	2.76E-03	0.0238	1.12E-03	0.0208	2.07E-04	0.0249	2.48	13.34	5.39
2 m	1.25E-03	0.0185	5.08E-04	0.0199	9.33E-05	0.0246	2.46	13.36	5.44
Point Detectors									
1 m	2.91E-03	0.0227	1.18E-03	0.0203	2.18E-04	0.0242	2.47	13.35	5.40
2 m	1.30E-03	0.0209	5.24E-04	0.0187	9.55E-05	0.0233	2.47	13.57	5.49

Source: Attachment II, *MCNP-Results1.xls,* worksheet *Summary.*

Tables 13, 14, and 15 are results of calculation set 1 for conceptual Cask A with axial profile sources in the active fuel region. The results include dose rates and dose-rate reduction factors between different PWR SNFs for the radial and axial directions of conceptual Cask A.

Table 16. Radial Dose Rates from Conceptual Cask A, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	2.65E-02	0.0247	9.90E-03	0.0222	2.15E-03	0.0278	2.68	12.34	4.61
1 m	1.16E-02	0.0178	4.68E-03	0.0549	9.60E-04	0.0189	2.48	12.08	4.88
2 m	7.13E-03	0.0273	2.65E-03	0.0161	6.02E-04	0.0360	2.69	11.84	4.39
Ring Detectors									
1 m	1.17E-02	0.0120	4.54E-03	0.0132	9.79E-04	0.0141	2.59	11.99	4.63
2 m	7.22E-03	0.0130	2.76E-03	0.0141	5.89E-04	0.0153	2.61	12.26	4.69

Source: Attachment II, *MCNP-Results2.xls,* worksheet *Summary.*

Table 17. Top Axial Dose Rates from Conceptual Cask A, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	1.99E-02	0.0461	8.27E-03	0.0455	1.47E-03	0.0536	2.41	13.59	5.64
1 m	8.49E-03	0.0564	3.23E-03	0.0314	5.63E-04	0.0418	2.63	15.07	5.74
2 m	4.15E-03	0.0832	1.58E-03	0.0603	2.53E-04	0.0501	2.63	16.41	6.23
Point Detectors									
1 m	8.77E-03	0.0348	3.53E-03	0.0275	6.15E-04	0.0391	2.48	14.26	5.74
2 m	3.93E-03	0.0341	1.60E-03	0.0278	2.70E-04	0.0378	2.46	14.54	5.90

Source: Attachment II, *MCNP-Results2.xls,* worksheet *Summary.*

Table 18. Bottom Axial Dose Rates from Conceptual Cask A, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	8.79E-03	0.0374	3.56E-03	0.0333	6.69E-04	0.0406	2.47	13.15	5.33
1 m	3.65E-03	0.0223	1.47E-03	0.0209	2.69E-04	0.0253	2.48	13.58	5.48
2 m	1.64E-03	0.0229	6.74E-04	0.0205	1.20E-04	0.0248	2.43	13.64	5.60
Point Detectors									
1 m	3.83E-03	0.0217	1.55E-03	0.0204	2.85E-04	0.0248	2.47	13.47	5.46
2 m	1.72E-03	0.0197	6.89E-04	0.0186	1.24E-04	0.0225	2.49	13.91	5.58

Source: Attachment II, *MCNP-Results2.xls,* worksheet *Summary.*

Tables 16, 17, and 18 are results of calculation set 2 for conceptual Cask A with uniform axial sources in the active fuel region. The results include dose rates and dose-rate reduction factors between different PWR SNFs for the radial and axial directions of conceptual Cask A.

7.1.2 Dose Rates of Conceptual Cask B

This section presents dose-rate results of the calculation sets 3 and 4 for conceptual Cask B. Set 3 has axial profile sources in the active fuel region and consist of six runs resulting from the three PWR SNF source terms (maximum, design basis, and average) and the two radiation sources (gammas and neutrons). Set 4 has uniform axial sources in the active fuel region and consists of six runs resulting from the three PWR SNF source terms and the two radiation sources.

Similar to conceptual Cask A, dose rates are calculated at the three exterior surfaces and at distances 1 m and 2 m from the exterior surfaces. The total dose rates for set 3 are presented in Tables 19, 20 and 21 for the radial, top, and bottom directions, respectively. However the components (primary gamma, neutron, and secondary gamma) contributing to the total dose rates as well as the relative error calculations can be found in Attachment II Excel file *MCNP-Results3.xls*, worksheets *Maximum, DesignBasis, and Average*. Similarly, the total dose rates for set 4 are shown in Tables 22, 23, and 24. The dose-rate components and the relative errors can be found in Attachment II Excel file *MCNP-Results4.xls,* worksheets *Maximum, DesignBasis, and Average*.

The surface tallies in Tables 19 and 22 are the radial total dose rates for the middle segment (at Z between 175 and 205 cm in Figure 1) at contact, 1 m, and 2 m from the radial surface. The surface tallies in Tables 20 and 23 are the top axial dose rates for the central segment within a 40-cm radius at contact and 1 m and 2 m from the top surface. Similarly, the surface tallies in Tables 21 and 24 are the bottom axial dose rates within a 40-cm radius.

This cask is expected to meet exterior radiation standards of 10 CFR 71.47(b) (Reference 2.3.1) when loaded with a TAD canister carrying the average PWR SNF. Based on the results in Tables 19 through 24, it is clear that all cask surface contact dose rates are less than 200 mrem/hr and that all 2-m dose rates are less than 10 mrem/hr. Therefore, conceptual Cask B indeed meets the 10 CFR 71.47(b) dose–rate requirements.

In these six tables, the dose-rate reduction factors between the maximum and the design basis fuels, the maximum and the average fuels, and the design basis and the average fuels are also presented.

Table 19. Radial Dose Rates from Conceptual Cask B, Axial Profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	2.37E-01	0.0321	8.69E-02	0.0319	1.67E-02	0.0437	2.73	14.24	5.22
1 m	1.04E-01	0.0228	3.72E-02	0.0224	7.59E-03	0.0339	2.79	13.69	4.90
2 m	6.26E-02	0.0230	2.30E-02	0.0226	4.30E-03	0.0346	2.73	14.55	5.34
Ring Detectors									
1 m	1.05E-01	0.0103	3.79E-02	0.0102	7.17E-03	0.0148	2.77	14.66	5.29
2 m	6.40E-02	0.0086	2.30E-02	0.0082	4.30E-03	0.0275	2.78	14.88	5.35

Source: Attachment II, *MCNP-Results3.xls,* worksheet *Summary.*

Table 20. Top Axial Dose Rates from Conceptual Cask B, Axial Profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	3.41E-01	0.0276	1.35E-01	0.0267	3.07E-02	0.0281	2.51	11.11	4.42
1 m	9.64E-02	0.0241	3.90E-02	0.0242	8.64E-03	0.0248	2.47	11.16	4.51
2 m	3.71E-02	0.0272	1.55E-02	0.0279	3.34E-03	0.0299	2.40	11.11	4.64
Point Detectors									
1 m	1.01E-01	0.0225	4.05E-02	0.0219	9.10E-03	0.0229	2.51	11.15	4.45
2 m	3.82E-02	0.0220	1.54E-02	0.0216	3.41E-03	0.0225	2.48	11.20	4.51

Source: Attachment II, *MCNP-Results3.xls,* worksheet *Summary.*

Table 21. Bottom Axial Dose Rates from Conceptual Cask B, Axial profile Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	2.13E-01	0.0178	8.42E-02	0.0177	2.01E-02	0.0180	2.53	10.59	4.19
1 m	7.03E-02	0.0132	2.79E-02	0.0132	6.66E-03	0.0136	2.52	10.56	4.19
2 m	2.86E-02	0.0131	1.13E-02	0.0132	2.70E-03	0.0135	2.53	10.59	4.19
Point Detectors									
1 m	7.44E-02	0.0130	2.94E-02	0.0130	7.05E-03	0.0134	2.53	10.56	4.17
2 m	2.95E-02	0.0126	1.17E-02	0.0125	2.79E-03	0.0130	2.52	10.56	4.19

Source: Attachment II, *MCNP-Results3.xls,* worksheet *Summary.*

Tables 19, 20, and 21 are results of calculation set 3 for conceptual Cask B with axial profile sources in the active fuel region. The results include dose rates and dose-rate reduction factors between different PWR SNFs for the radial and axial directions of conceptual Cask B.

Table 22. Radial Dose Rates from Conceptual Cask B, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	2.08E-01	0.0355	7.31E-02	0.0349	1.35E-02	0.0461	2.85	15.38	5.40
1 m	9.44E-02	0.0235	3.36E-02	0.0240	6.28E-03	0.0316	2.81	15.04	5.36
2 m	6.09E-02	0.0238	2.17E-02	0.0228	4.08E-03	0.0342	2.80	14.94	5.33
Ring Detectors									
1 m	9.70E-02	0.0119	3.45E-02	0.0179	6.43E-03	0.0182	2.81	15.09	5.37
2 m	6.07E-02	0.0089	2.18E-02	0.0097	4.03E-03	0.0143	2.78	15.06	5.42

Source: Attachment II, *MCNP-Results4.xls,* worksheet *Summary.*

Table 23. Top Axial Dose Rates from Conceptual Cask B, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	6.12E-01	0.0219	2.50E-01	0.0219	6.27E-02	0.0219	2.44	9.76	3.99
1 m	1.74E-01	0.0191	6.96E-02	0.0196	1.74E-02	0.0198	2.50	10.02	4.01
2 m	6.65E-02	0.0214	2.71E-02	0.0233	6.65E-03	0.0216	2.45	10.00	4.08
Point Detectors									
1 m	1.82E-01	0.0174	7.34E-02	0.0181	1.82E-02	0.0179	2.48	9.99	4.02
2 m	6.87E-02	0.0172	2.73E-02	0.0173	6.81E-03	0.0178	2.51	10.08	4.01

Source: Attachment II, *MCNP-Results4.xls,* worksheet *Summary.*

Table 24. Bottom Axial Dose Rates from Conceptual Cask B, Uniform Axial Sources

	Maximum Fuel		**Design Basis Fuel**		**Average Fuel**		**Dose-Rate Reduction Factor**		
	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Dose Rate (rem/hr)	Relative Error	Max/DB	Max/Ave	DB/Ave
Surface Tallies									
Contact	3.10E-01	0.0156	1.24E-01	0.0156	2.90E-02	0.0155	2.51	10.70	4.27
1 m	1.05E-01	0.0114	4.17E-02	0.0113	9.76E-03	0.0113	2.50	10.71	4.28
2 m	4.27E-02	0.0116	1.71E-02	0.0115	4.00E-03	0.0113	2.49	10.67	4.28
Point Detectors									
1 m	1.11E-01	0.0112	4.41E-02	0.0112	1.04E-02	0.0113	2.51	10.70	4.26
2 m	4.41E-02	0.0108	1.76E-02	0.0108	4.11E-03	0.0109	2.51	10.73	4.28

Source: Attachment II, *MCNP-Results4.xls,* worksheet *Summary.*

Tables 22, 23, and 24 are results of calculation set 4 for conceptual Cask B with uniform axial sources in the active fuel region. The results include dose rates and dose-rate reduction factors between different PWR SNFs for the radial and axial directions of conceptual Cask B.

7.1.3 Comparison of Dose-Rate Reduction Factors

This section examines the effects of the source axial distributions and the configurations of the conceptual casks on the dose-rate reduction factors in the radial, top, and bottom directions outside the two conceptual casks. The dose-rate reduction factors in Tables 13 through 24 are rearranged for clarity.

Tables 25 and 26 compare the dose-rate reduction factors in the radial direction for conceptual Casks A and B with axial source profiles and with uniform axial sources, respectively. In these two tables, the dose-rate reduction factors from averaging Casks A and B are also computed. Furthermore, for each dose-rate reduction factor the average value from all five tallies are provided. Similarly, Tables 27 and 28 present the dose-rate reduction factors in the top direction, and Tables 29 and 30 give the dose-rate reduction factors in the bottom direction.

Starting with the radial direction in Tables 25 and 26, it is noted that the effect of the axial source distributions on the reduction factors is small, but the effect of the conceptual cask configuration is more pronounced. For example, the average dose-rate reduction factors Max/DB, Max/Ave and DB/Ave for conceptual Cask A in Table 25 (bottom row) are 2.70, 12.49 and 4.63, respectively. The same factors for conceptual Cask B in Table 26 (bottom row) are 2.61, 12.10, and 4.64. Generally speaking, these two sets of reduction factors are quite close. On the other hand, a comparison of the first set of factors for conceptual Cask A in Table 25 (2.70, 12.49 and 4.63) with the set for conceptual Cask B in Table 25 (2.76, 14.40, and 5.22) indicates that the difference between the two sets is larger. Similarly, same conclusion can be reached between conceptual Casks A and B in Table 26.

The small effect of the axial source distributions to the reduction factors can be attributed to the fact that the same axial distributions, whether uniform or axial profiles, are applied to all three PWR SNF source terms. The influence of the axial distributions on the dose rates from different PWR SNF source terms is nearly linear and therefore cancels out because the reduction factors are the ratio of dose rates from different source terms. In contrast, the configurations of the conceptual casks affect the dose rates from different PWR SNF source terms in a non-linear manner since radiation attenuation in the materials of the casks has a non-linear behavior, either exponential or otherwise.

Table 25. Radial Dose-Rate Reduction Factors for Casks with Axial Profile Sources

	Cask A (Set 1)			Cask B (Set 3)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.75	12.23	4.45	2.73	14.24	5.22	2.74	13.23	4.83
1 m (Surface)	2.69	12.61	4.68	2.79	13.69	4.90	2.74	13.15	4.79
2 m (Surface)	2.63	12.82	4.88	2.73	14.55	5.34	2.68	13.68	5.11
1 m (Ring)	2.71	12.29	4.54	2.77	14.66	5.29	2.74	13.47	4.92
2 m (Ring)	2.71	12.50	4.62	2.78	14.88	5.35	2.74	13.69	4.98
Average	2.70	12.49	4.63	2.76	14.40	5.22	2.73	13.45	4.93

Source: Attachment II, *DR-Ratios.xls,* worksheet *Radial.*

Table 26. Radial Dose-Rate Reduction Factors for Casks with Uniform Axial Sources

	Cask A (Set 2)			Cask B (Set 4)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.68	12.34	4.61	2.85	15.38	5.40	2.76	13.86	5.00
1 m (Surface)	2.48	12.08	4.88	2.81	15.04	5.36	2.64	13.56	5.12
2 m (Surface)	2.69	11.84	4.39	2.80	14.94	5.33	2.75	13.39	4.86
1 m (Ring)	2.59	11.99	4.63	2.81	15.09	5.37	2.70	13.54	5.00
2 m (Ring)	2.61	12.26	4.69	2.78	15.06	5.42	2.70	13.66	5.05
Average	2.61	12.10	4.64	2.81	15.10	5.37	2.71	13.60	5.01

Source: Attachment II, *DR-Ratios.xls,* worksheet *Radial.*

Table 27. Top Dose-Rate Reduction Factors for Casks with Axial Profile Sources

	Cask A (Set 1)			Cask B (Set 3)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.26	15.20	6.72	2.51	11.11	4.42	2.39	13.15	5.57
1 m (Surface)	2.17	15.20	7.01	2.47	11.16	4.51	2.32	13.18	5.76
2 m (Surface)	2.16	15.75	7.30	2.40	11.11	4.64	2.28	13.43	5.97
1 m (Point)	2.19	14.89	6.81	2.51	11.15	4.45	2.35	13.02	5.63
2 m (Point)	2.21	15.15	6.84	2.48	11.20	4.51	2.35	13.18	5.68
Average	2.20	15.24	6.94	2.47	11.15	4.51	2.34	13.19	5.72

Source: Attachment II, *DR-Ratios.xls,* worksheet *Top.*

Table 28. Top Dose-Rate Reduction Factors for Casks with Uniform Axial Sources

	Cask A (Set 2)			Cask B (Set 4)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.41	13.59	5.64	2.44	9.76	3.99	2.43	11.67	4.82
1 m (Surface)	2.63	15.07	5.74	2.50	10.02	4.01	2.56	12.55	4.87
2 m (Surface)	2.63	16.41	6.23	2.45	10.00	4.08	2.54	13.20	5.15
1 m (Point)	2.48	14.26	5.74	2.48	9.99	4.02	2.48	12.13	4.88
2 m (Point)	2.46	14.54	5.90	2.51	10.08	4.01	2.49	12.31	4.96
Average	2.52	14.77	5.85	2.48	9.97	4.02	2.50	12.37	4.94

Source: Attachment II, *DR-Ratios.xls,* worksheet *Top.*

Table 29. Bottom Dose-Rate Reduction Factors for Casks with Axial Profile Sources

	Cask A (Set 1)			Cask B (Set 3)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.47	12.78	5.18	2.53	10.59	4.19	2.50	11.69	4.69
1 m (Surface)	2.48	13.34	5.39	2.52	10.56	4.19	2.50	11.95	4.79
2 m (Surface)	2.46	13.36	5.44	2.53	10.59	4.19	2.49	11.98	4.81
1 m (Point)	2.47	13.35	5.40	2.53	10.56	4.17	2.50	11.96	4.79
2 m (Point)	2.47	13.57	5.49	2.52	10.56	4.19	2.50	12.07	4.84
Average	2.47	13.28	5.38	2.53	10.57	4.19	2.50	11.93	4.78

Source: Attachment II, *DR-Ratios.xls,* worksheet *Bottom.*

Table 30. Bottom Dose-Rate Reduction Factors for Casks with Uniform Axial Sources

	Cask A (Set 2)			Cask B (Set 4)			Average of Casks A & B		
Tally Type	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**	**Max/DB**	**Max/Ave**	**DB/Ave**
Contact (Surface)	2.47	13.15	5.33	2.51	10.70	4.27	2.49	11.92	4.80
1 m (Surface)	2.48	13.58	5.48	2.50	10.71	4.28	2.49	12.14	4.88
2 m (Surface)	2.43	13.64	5.60	2.49	10.67	4.28	2.46	12.16	4.94
1 m (Point)	2.47	13.47	5.46	2.51	10.70	4.26	2.49	12.08	4.86
2 m (Point)	2.49	13.91	5.58	2.51	10.73	4.28	2.50	12.32	4.93
Average	2.47	13.55	5.49	2.50	10.70	4.27	2.49	12.13	4.88

Source: Attachment II, *DR-Ratios.xls,* worksheet *Bottom.*

The recommended average dose-rate reduction factors of Casks A and B are summarized in Tables 31, 32, and 33 for the radial, top, and bottom directions, respectively.

Table 31. Recommended Average Radial Dose-Rate Reduction Factors

	Max/DB	**Max/Ave**	**DB/Ave**
Axial Profile Sources	2.7	13.5	4.9
Uniform Axial Sources	2.7	13.6	5.0

Table 32. Recommended Average Top Dose-Rate Reduction Factors

	Max/DB	**Max/Ave**	**DB/Ave**
Axial Profile Sources	2.3	13.2	5.7
Uniform Axial Sources	2.5	12.4	4.9

Table 33. Recommended Average Bottom Dose-Rate Reduction Factors

	Max/DB	**Max/Ave**	**DB/Ave**
Axial Profile Sources	2.5	11.9	4.8
Uniform Axial Sources	2.5	12.1	4.9

7.2 CONCLUSIONS

This calculation has been performed with the assumed configurations for a TAD canister and two conceptual transportation casks, Cask A designed to meet the 10 CFR 71.47(b) radiation standards with the maximum CSNF PWR assemblies and Cask B with the average CSNF PWR assemblies. The dose rate reduction factors between different source terms, with and without axial profiles, have been computed for the radial, top, and bottom directions of the conceptual TAD transportation casks. The average dose-rate reduction factors for the radial and axial directions of the conceptual casks are summarized in Tables 31, 32, and 33. Generally, the average radial reduction factor between the maximum and the design basis fuels is 2.7. The average top reduction factor between the maximum and the design basis fuels is 2.4, and the average bottom reduction factor between the maximum and the design basis fuels is 2.5. The average dose-rate reduction factors for other combinations of source terms are substantially higher and are shown in Tables 31, 32, and 33.

ATTACHMENT I ELECTRONIC FILES ON COMPACT DISC

This attachment contains a description of electronic files for this calculation. The electronic files are stored in a CD that is Attachment II of this calculation.

In Table I-1, the Excel files *MCNP-Results#.xls* are summaries of MCNP5 results where "#" is the calculation set number described in Section 6.1. The Excel file *DR-Ratios.xls* calculates the dose-rate ratios between different source terms. The Excel file *Geometry.xls* prepares and calculates tally areas for MCNP5 input. The Excel file *PWR_fuel comp.xls* calculates the atomic densities of materials for MCNP5 input. Also, the files in the folders *max*, *dsb*, and *ave* are MCNP5 input and output files for runs with either neutron source or gamma source. The files with an "o" at the end are the MCNP5 output files. Again, the number in each file name corresponds to the calculation set number described in Section 6.1.

Table I-1. Listing of Electronic Files on Compact Disc

Volume in drive D is DR-RECUCTIONFACT
Volume Serial Number is AEA2-ACF5

Directory of D:\CD

11/19/2008 02:30 PM <DIR> .
11/20/2008 03:45 PM <DIR> ..
11/13/2008 07:49 AM <DIR> ave
11/19/2008 02:30 PM 37,376 DR-Ratios.xls
11/13/2008 07:51 AM <DIR> dsb
11/13/2008 04:29 PM 23,552 Geometry.xls
11/19/2008 03:45 PM <DIR> max
11/14/2008 08:24 AM 54,272 MCNP-Results1.xls
11/17/2008 05:21 PM 55,808 MCNP-Results2.xls
11/14/2008 08:31 AM 57,344 MCNP-Results3.xls
11/17/2008 05:32 PM 55,296 MCNP-Results4.xls
09/28/2008 11:18 AM 73,728 PWR_fuel comp.xls
7 File(s) 357,376 bytes
5 Dir(s) 0 bytes free

Directory of D:\CD\max

11/19/2008 03:45 PM <DIR> .
11/19/2008 02:30 PM <DIR> ..
10/29/2008 12:56 PM 20,049 neut1
11/01/2008 10:07 AM 1,373,477 neut1o
09/28/2008 10:56 AM 19,865 neut2
10/01/2008 05:58 AM 1,352,463 neut2o
11/07/2008 03:22 PM 18,700 neut3

```
11/10/2008  02:18 AM         1,360,249 neut3o
11/07/2008  03:50 PM            18,442 neut4
11/10/2008  02:20 AM         1,366,121 neut4o
10/29/2008  12:28 PM            15,502 pgam1
10/31/2008  12:47 AM         1,020,042 pgam1o
09/28/2008  10:56 AM            15,288 pgam2
09/29/2008  08:38 PM           994,975 pgam2o
11/07/2008  03:22 PM            14,247 pgam3
11/08/2008  04:57 PM           964,365 pgam3o
11/07/2008  03:33 PM            13,993 pgam4
11/08/2008  04:59 PM           953,276 pgam4o
              16 File(s)      9,521,054 bytes
               2 Dir(s)               0 bytes free

 Directory of D:\CD\dsb

11/13/2008  07:51 AM    <DIR>          .
11/19/2008  02:30 PM    <DIR>          ..
10/29/2008  03:10 PM            20,082 neut1
11/01/2008  10:09 AM         1,396,700 neut1o
09/28/2008  10:56 AM            19,897 neut2
10/01/2008  05:57 AM         1,370,656 neut2o
11/07/2008  03:44 PM            18,736 neut3
11/10/2008  02:22 AM         1,383,127 neut3o
11/07/2008  03:53 PM            18,476 neut4
11/10/2008  02:23 AM         1,372,810 neut4o
10/29/2008  03:18 PM            15,466 pgam1
10/31/2008  12:48 AM         1,012,478 pgam1o
09/28/2008  10:56 AM            15,252 pgam2
09/29/2008  08:37 PM           990,329 pgam2o
11/07/2008  03:27 PM            14,214 pgam3
11/08/2008  05:02 PM           956,299 pgam3o
11/07/2008  03:36 PM            13,957 pgam4
11/08/2008  05:03 PM           953,725 pgam4o
              16 File(s)      9,572,204 bytes
               2 Dir(s)               0 bytes free

 Directory of D:\CD\ave

11/13/2008  07:49 AM    <DIR>          .
11/19/2008  02:30 PM    <DIR>          ..
10/29/2008  03:11 PM            20,086 neut1
11/06/2008  11:02 AM         1,358,810 neut1o
09/28/2008  10:54 AM            19,900 neut2
10/01/2008  05:56 AM         1,376,788 neut2o
11/07/2008  03:48 PM            18,739 neut3
```

```
11/10/2008  02:25 AM         1,357,396 neut3o
11/07/2008  03:54 PM            18,484 neut4
11/10/2008  02:25 AM         1,352,112 neut4o
10/29/2008  03:17 PM            15,454 pgam1
11/05/2008  01:41 AM         1,002,114 pgam1o
09/28/2008  10:54 AM            15,240 pgam2
09/29/2008  08:35 PM         1,008,401 pgam2o
11/07/2008  03:30 PM            14,202 pgam3
11/08/2008  05:04 PM           961,904 pgam3o
11/07/2008  03:38 PM            13,950 pgam4
11/08/2008  05:05 PM           964,756 pgam4o
              16 File(s)      9,518,336 bytes
               2 Dir(s)               0 bytes free
```